Mine Burial by Local Scour and Sand Waves

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LONG-TERM GOALS

Our long term goal is to help advance the U.S. Navy's capabilities for Mine Burial Prediction (MBP) by conducting large-scale laboratory observations that will both improve our knowledge of the physical processes involved in mine burial and provide a vital bridge between field experiments and numerical modeling of mine burial processes in shallow waters.

OBJECTIVES

The main objective of this effort has been the direct observation and monitoring of the burial process of finite-length cylinders (model mines) induced by the combined action of waves, currents and pure oscillatory flows. The experimental conditions have made it possible to observe the burial process due to both local scour around the mines as well as the passage of large sand waves. These rather unique observations will be used to test, validate, and calibrate numerical model predictions and will also help in the development of a mechanistic model for Mine-Fluid-Sediment (MFS) interaction by the ONR Mine Burial Prediction Team.

APPROACH

Our approach has been mainly an experimental one. We have conducted laboratory experiments with two special-purpose facilities. One facility is the Large Oscillating Water Sediment Tunnel (LOWST) constructed with DURIP support. LOWST can reproduce field-like conditions near the sea bed. The second facility is a multipurpose wave-current flume which is 4 feet (1.20 m) deep, 6 feet (1.8 m) wide, and 161 feet (49.2 m) long. It has a 45 cm deep movable sediment bed where model mines can be placed and scour tests conducted under the action of waves and currents. Experiments have been conducted with both a single mine as well as multiple mines. This approach has been particularly useful to assess the role of sand waves in the burial process.

Our research team consists of the PI and three Graduate Research Assistants, Yovanni Catano (PhD Candidate), Xiaofeng Liu (PhD Student) and Salih Demir (MS Student). We have also collaborated with Dr. David Admiraal (University of Nebraska) and Dr. Yarko Nino (University of Chile), in the development of Particle-Image-Velocimetry (PIV) techniques to monitor the flow velocity field around model mines and sand ripples.

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WORK COMPLETED

Wave Tank: More than a hundred experiments were carried out in the wave-current flume. The main task completed within this effort has been the characterization of the burial process in the presence of dynamic sand waves with superimposed ripples. It is found that the burial of a finite-length cylinder is determined by local scour around the cylinder and by a more global process associated with the formation and evolution of sand waves having superimposed ripples on them. Depending on the ratio of the amplitude of these features and the body's diameter (*D*), a model mine can progressively get partially or totally buried as such bed forms migrate. Experiments were conducted in the range of wave Reynolds number $7.1 \times 10^3 < R_e < 6 \times 10^5$, and Keulegan-Carpenter number $2 \leq KC \leq 26$. Analysis of the experimental data indicates that existing semi-empirical formulae for prediction of equilibrium-burial-depth and time-scales developed for pipelines are not suitable for the case of a cylinder of finite length.

Oscillatory-flow tunnel: about 18 experiments have been completed with LOWST. Mainly, burial due to scour under pure oscillatory motion was studied. Observations were made with two camcorders, one in each side of the model cylinder during the scour and burial process. Three different model cylinders (mines) were tested in the range of $11 < KC < 55$. Interestingly, length to diameter ratio, density and initial burial of the models were found to be ineffective on the final burial depth. The scour process for cylindrical objects is clearly identified. Currently used Carstens&Martin and HR Wallingford burial equations were tested and found to be inadequate for burial estimations in our experiments. A new equation for estimating the final burial depth is proposed.

RESULTS

Wave Tank Results: Relative burial depth (B_d/D) is found to be mainly a function of two parameters. One is the Keulegan-Carpenter number, *KC,* (Fig.1), and the Shields parameter, θ (Fig. 2). Data scatter is less for the latter case where also although with similar trends a clear distinction is present for both, waves alone and combined flows. A similar behavior is observed when plotting relative burial depth as a function of the cylinder Reynolds wave number, R_e, (Fig. 3). In both cases the trend for combined flows is below the one for waves alone. Combining both, θ and *KC* it is observed that all measured data can be represented by the following expression $B_d / D = \varepsilon\left(1 - e^{-m(KC-KC_{cr})} e^{-n(\theta-\theta_{cr})}\right)$, where ε, *m* and, *n* are empirical coefficients. $KC_{crit} \approx 2.0$ and, $\theta_{cr} \approx 0.018$ are the critical Keulegan-Carpenter number and critical Shields parameter, respectively. One can conclude that such expression does a fairly good job for prediction purposes, Fig. 4. Burial-time scales seem to be influenced by both *KC* and the Shields parameter, θ, as shown in Fig.5.

Development and evolution of sand waves has been identified as a major agent on the global mine burial process. Ripples superimposed on sand waves vary in size and shape depending on their relative position along the sand wave. The study of both types of features is of vital importance for the proper understanding of the flow-bed interaction and the resulting bed morphodynamics. The evolution and shape of bed forms influence the flow pattern over the bed and the flow interacting with the cylindrical object. The present experimental work has also been extended to the study of formation and evolution of both, ripples and sand waves. Experimental data had been collected describing length, height, steepness and migration speed. For instance, Figure 6 shows measured migration speeds for sand waves. In particular sand wave size and migration speeds seem to play a major role in the mine burial process due to progressive covering and uncovering of the cylinder. Once they start development, it can be observed that they travel in the direction of the wave propagation. Sand waves have a very well defined sinusoidal pattern when pure wave motion is imposed, however for the case of waves plus currents they start to emulate the shape of dunes as in the case of unidirectional flow. Existing predictive formulae for sand wavelength and migration speed deduced from analytical analysis, in particular those dealing with linear and weakly nonlinear analysis; seem not to be in good agreement with the present experimental data.

Preliminary analysis suggests that the mean ratio of the wavelength of sand waves to the length of superimposed ripples is $L_{sw}/L_r \approx O$ (15-60). On the other hand, the effect of ripples is not predominant in the burial process when ripple dimensions are much smaller than those of the mine. Our experiments on waves alone and combined flow support this conclusion. One of the reasons for the ripple effect not to be very significant is that ripples are not formed in the neighborhood of the cylinder due to the redistribution of the flow field surrounding the body, which prevents their formation. It was observed that ripples travel at varying speeds, but normally of the order of 1 to 2 cm/minute. In order to study sand waves and ripples characteristics and their incidence on the general scour/sinking process five cylinders were placed on the sandy bottom separated by a distance of about 70 cm from each other along the flume centerline. To this end, a couple of long duration experiments were conducted for both cases waves alone and combined flow conditions. The flow and waves characteristics were: h = 56 cm, A_w = 19.6 cm, L_w = 4.3 m, T_w = 2.04 s, and a mean velocity of U = 17 cm/s, for the latter case. All cylinders were made of concrete with D = 15.2 cm and a length of 30.5 cm. The results are summarized in Figures 7 and 8. Notice in Fig. 7 the progression of a sand wave with an almost perfect sinusoidal shape in the downstream direction with an average migration speed of 0.3 cm/min. Superimposed ripples travel also in the downstream direction with an average speed of 1.2 cm/min. Notice that the amplitude of the sand wave is larger than the cylinder diameter D = 15.2 cm. It is observed that after about 34 hrs the rightmost mine started to be uncovered. Notice also that the scour pattern around each specimen is different depending on its particular location along the sand wave. Plots of bottom profiles for the case of combined flow are shown in Fig. 8. In this case the sand wave pattern is rather complex, when compared with the previous case. A better idea of the resulting morphology observed at the end of both experiments can be obtained by observing Fig. 9. At the end of the experiments, all but two of the model mines have been completely buried for the case of waves alone. On the other hand, all the model mines are still visible in the case of combined wave-current conditions as seen in Fig. 9.

Oscillatory Tunnel Results: Experimental observations showed that the main mechanism of burial by scour is as follows; Scour starts from the shoulders of the cylinder and tends to move towards the center. As the net downward force on the cylinder exceeds the bearing capacity of the remaining soil beneath the cylinder, sinking occurs. Since it is nearly impossible to have a perfectly symmetric scour shape, one end of the cylinder falls into the scour pit first and this causes small tilting of the model cylinder. After a while, the other end of the cylinder falls. This process, sinking of one end followed by the other (with decreasing increments, but in a much slower way) repeats itself many times. After this point, two different burial mechanisms were observed as follows:

1) The process might continue as described above until final burial depth. (Figure 10a) In the final burial state, the maximum scour depth is located at the ends of the cylinder and some sand is accumulated in the middle at a height of around half the cylinder diameter.

2) Sinking of one end of the cylinder might not be compensated with the sinking of the other end. In this case, the model stays tilted, without regaining a horizontal position. (Figure 10b) Generally, this type of behavior was seen at high flow conditions.

It is found that the main parameter affecting the final burial depth of a finite length cylindrical object lying on a sandy sea bottom under wave action is the Shields parameter. (Figure 11) However, the burial time-scale seems to depend on more than one parameter. Studies are still being done to fully understand the time scale of the burial process.

IMPACT/APPLICATIONS

Our observations indicate that the mine burial mechanism is a complex process. Mine burial under either waves or combined flow, is influenced by two different processes. One is related to the *local scour* around the mine, which takes place within the first few hundred minutes of flow action (i.e. short time scale). Another process that can influence the final burial depth has been identified and is related to the development of sand waves which in turn may partially or totally cover a given mine as they migrate (i.e. long time scales). This process could be dubbed as *global burial*. Existing formulations for mine burial do not account for the dynamics of long sand waves, thus suggesting that a probabilistic approach would have to be followed in order to predict the vertical displacement and burial of a given mine. Our findings suggest the need to produce two kinds of models for mine burial prediction. The first kind should be able to reproduce local scour around an object (i.e. mine) for small space and time scales. The second kind should be capable of predicting the dynamics of long sand waves, including their interaction with bottom objects, over much larger space and time scales. ONR's Mine Burial Prediction Program has ongoing efforts along these modeling approaches. The observations reported herein can be used to test and improve such models.

RELATED PROJECTS

Within the Mine Burial Prediction Program there are a number of related projects. In particular, Diane Foster of Ohio State University plans to use our observations to test and calibrate a model for sediment scour around mines. The experimental work being conducted at the Arizona State University by H.J. Fernando and S. Voropayev complements our experimental observations.

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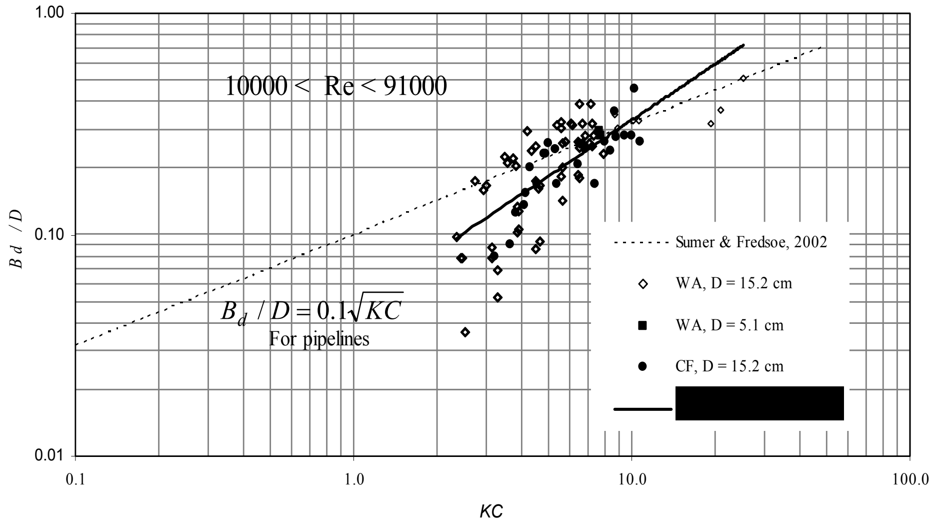


Fig. 1. Equilibrium relative burial depth as function of the KC number for a cylinder placed on the sand bed. Waves alone and combined flow, live bed ($\theta > \theta_{cr}$)

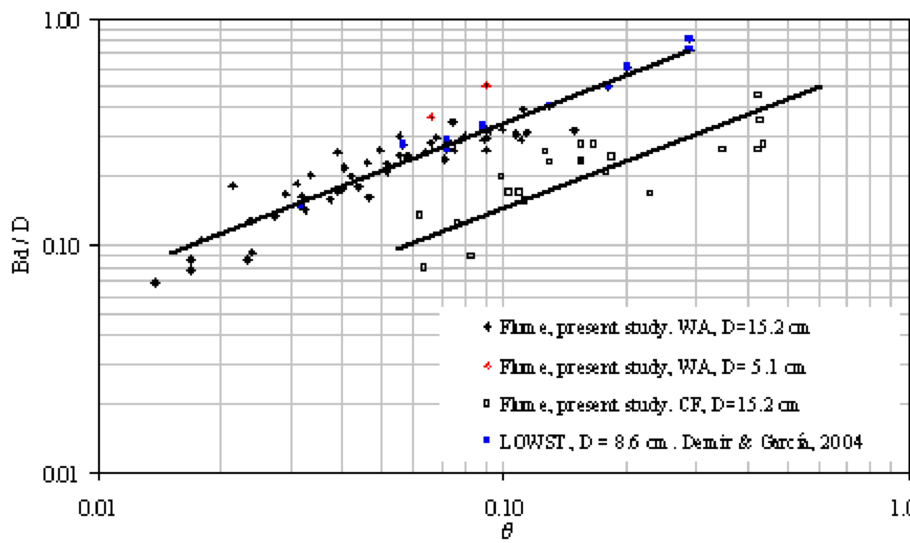


Fig. 2. Equilibrium burial depth as a function of the Shields Parameter θ. Waves alone and combined flow on the free surface flume and the Oscillatory Tunnel (LOWST), live bed ($\theta > \theta_{cr}$).

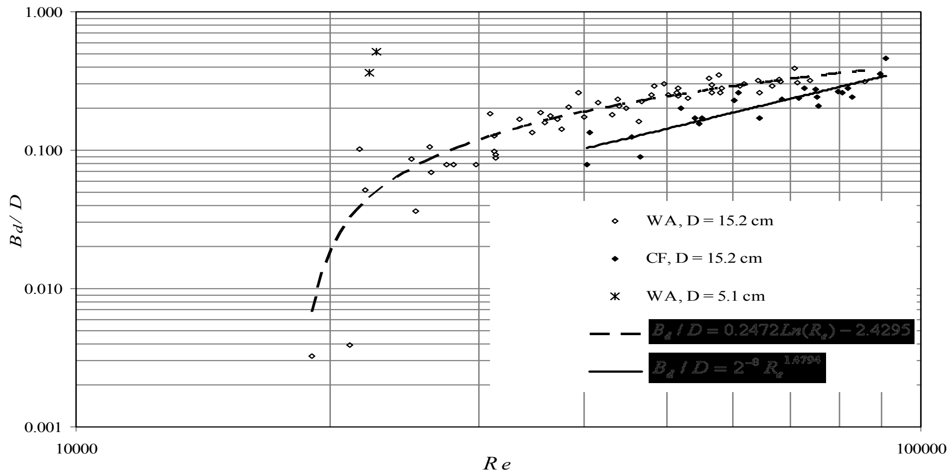


Fig. 3. Equilibrium burial depth as function of the cylinder Reynolds wave number. Both cases: waves alone and combined flow, live bed ($\theta > \theta_{cr}$).

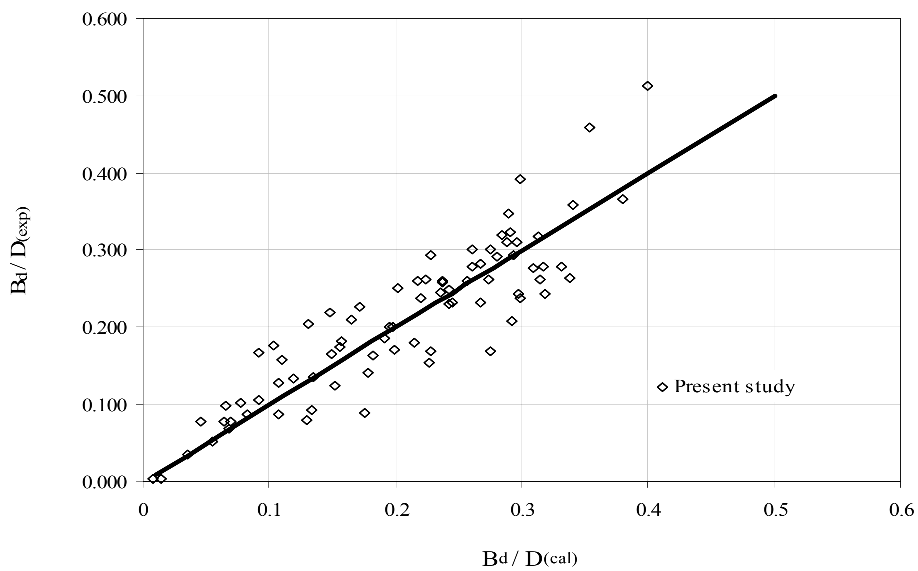


Fig.4. Experimental data compared with predictions with $B_d / D = \varepsilon\left(1 - e^{-m(KC - KC_{cr})} e^{-n(\theta - \theta_{cr})}\right)$***, for both, waves alone and combined flow.***

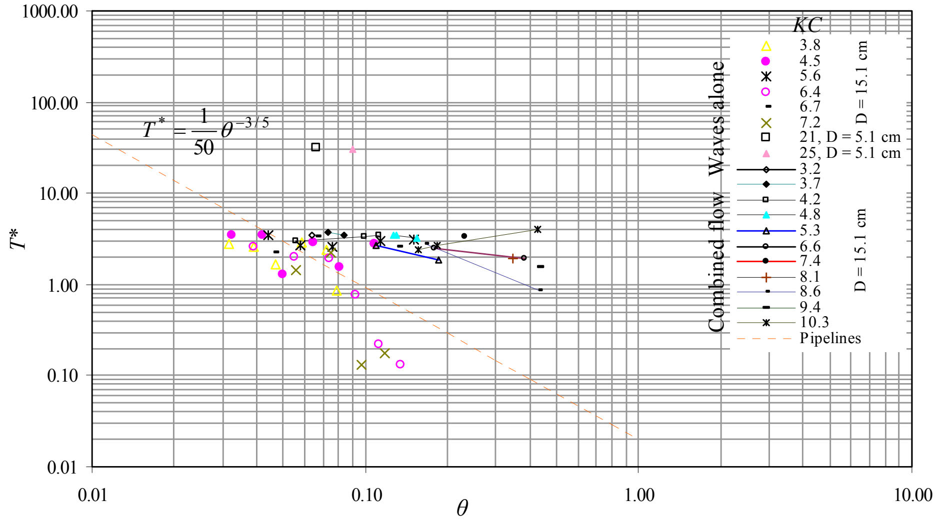


Fig. 5. Dimensionless time scale T* as function of the Shields parameter, θ, and the Keulegan-Carpenter number, KC. Waves alone and Combined flow, D = 15.2 cm, Live bed, ($\theta > \theta_{cr}$). Comparison with the case of self-burial of pipelines at span shoulders in a steady current, Sumer and Fredsoe (2002).

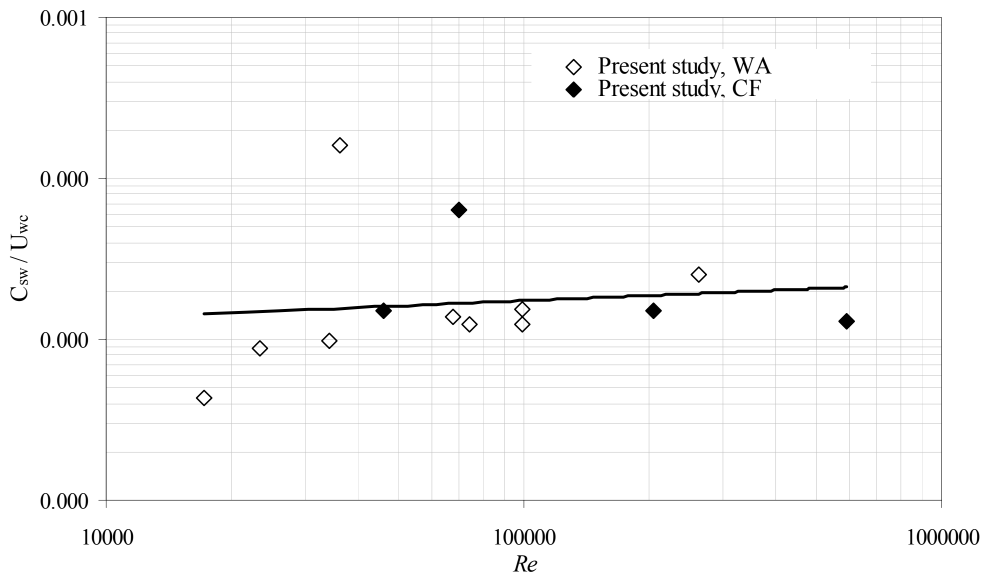


Fig. 6. Sand wave migration speed as a function of the Reynolds wave number, $R_e = U\,a / \nu$, in which a is the particle orbital wave amplitude.

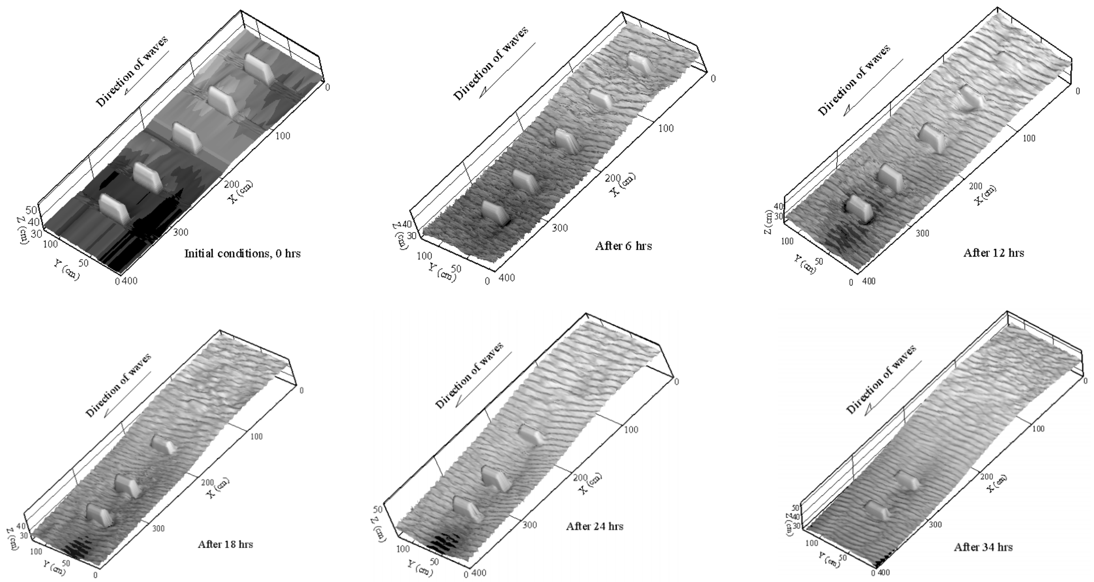


Fig. 7. Evolution over time of scour pattern and migration of ripples superimposed on sand waves. Water waves without current. Conditions: $D = 15.2$ cm, $h = 56$ cm, $A_w = 19.6$ cm, $L_w = 4.3$ m, $T_w = 2.04$ s

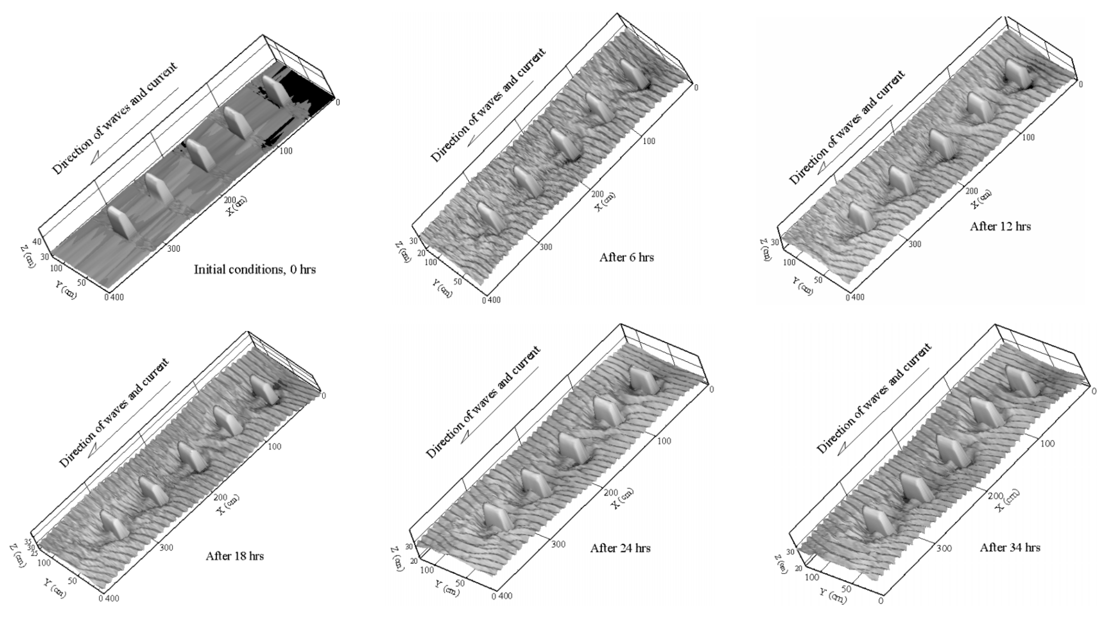


Fig. 8. Evolution over time of scour pattern and migration of ripples superimposed on sandwaves. Case of combined flow. Conditions: $D = 15.2$ cm, $h = 56$ cm, $A_w = 19.6$ cm, $L_w = 4.3$ m, $T_w = 2.04$ s, $U = 17$ cm/s

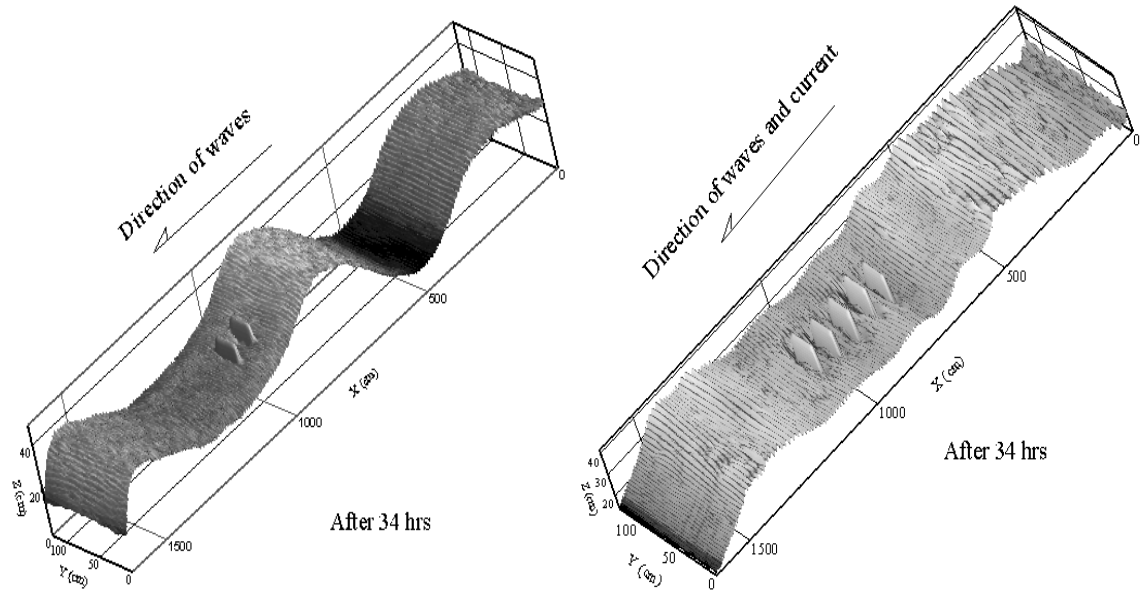
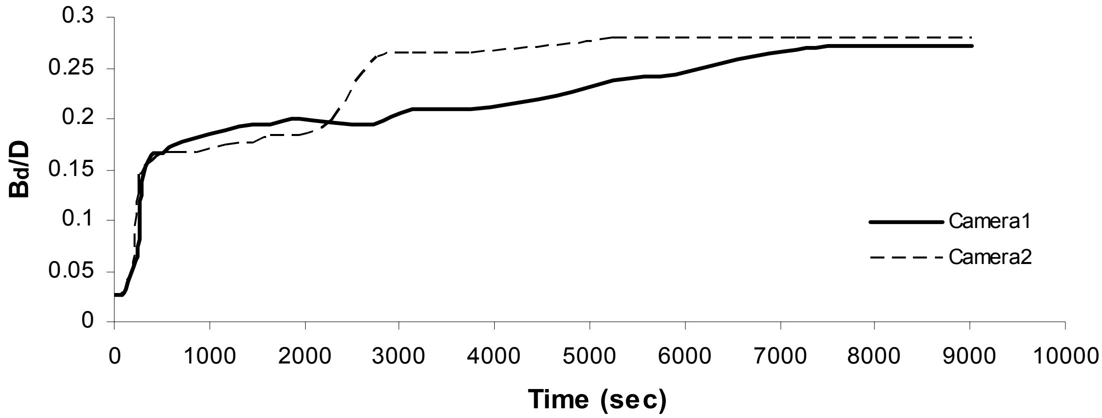
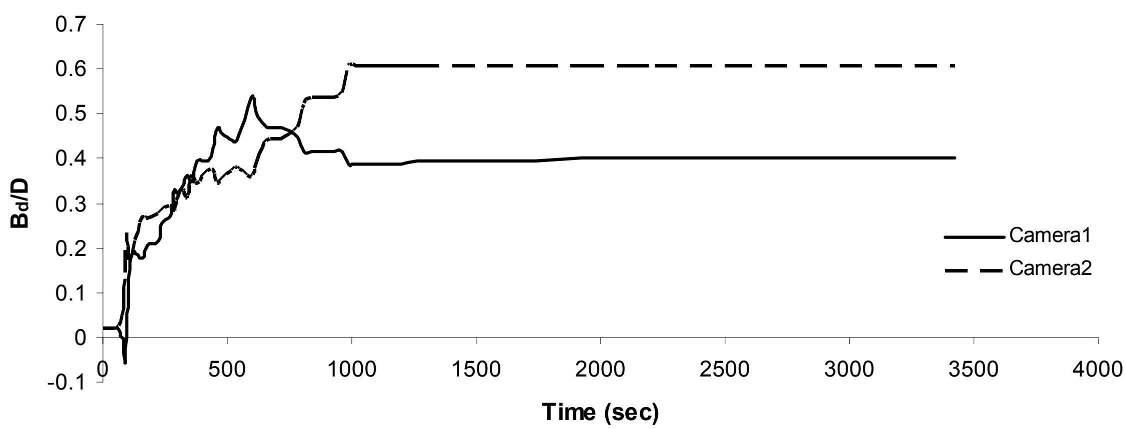


Fig. 9. Bed morphology after 34 hours. Cases: (Left) waves alone; (right) combined flow. Conditions correspond to those showed in Figs. 4 and 5, respectively.



a)Umax=25cm/s Period=4 sec



b)Umax=50 cm/s Period=9 sec

Fig. 10. Evolution of cylinder burial over time. (Pure oscillatory flow)

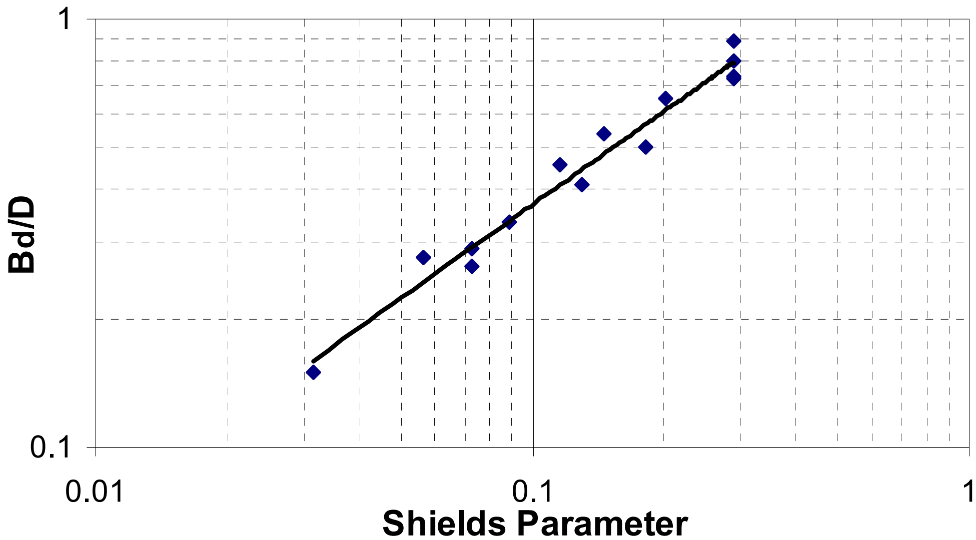


Fig. 11. Equilibrium relative burial depth (Bd/D) versus shields parameter